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FRAGMENTATION OF MOLECULAR CLOUDS: THE INITIAL PHASE OF A STELLAR CLUSTER

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Abstract. Using smoothed particle hydrodynamics in combination with the special-purpose hardware device Grape, we follow the fragmentation process and dynamical evolution in the interior of molecular clouds until most of the gas is converted to form a cluster of protostellar cores. The properties of this protostellar cluster are compared to observational data from star forming regions.

1. Introduction

The dynamical evolution and fragmentation in molecular clouds is a very complex process leading to the formation of stars. It involves a wide range of physical phenomena and spans many orders of magnitude in gas density. Molecular clouds have very complicated structure. Observations reveal a hierarchy of clumps and sub-clumps on all scales accessible by today's telescopes.

To examine this problem, we start in the most basic way: We follow the evolution of a region in the interior of a molecular cloud using smoothed particle hydrodynamics (Benz 1990, Monaghan 1992) in combination with the special-purpose hardware device Grape (Sugimoto et al. 1990, Ebisuzaki et al. 1993). Periodic boundary conditions prevent global collapse of the system (Klessen 1997). Grape solves Poisson's equation by direct summation and returns a list of nearest neighbors for each particle, which makes it suitable for combination with SPH. To start with, we adopt a simple isothermal model, and thus concentrate on the interplay between gravity and gas pressure. This produces a hierarchical network of filaments, sheets

and collapsing protostellar knots. In our simulations, once a collapsed core has formed, we replace it by a 'sink' particle that has the ability to accrete from its surrounding gaseous envelope (Bate et al. 1995). Starting from Gaussian initial density perturbations we follow the evolution of the system until most gas is consumed by the newly formed cluster of protostars.

Our goal is to find a description of how the formation of these objects and their properties depend on the initial conditions. Hence, we follow the fragmentation process for a range of *temperatures* and different sets of *initial density fields* (typically Gaussian with varying power laws or turbulent velocity structure).

These clusters of accreting protostellar clumps have to be compared with the observational data in star forming regions: Mass spectra, kinematical properties, multiplicity and spatial distribution can be used to constrain the physical model and exclude regions in parameter space that cannot reproduce the observations.

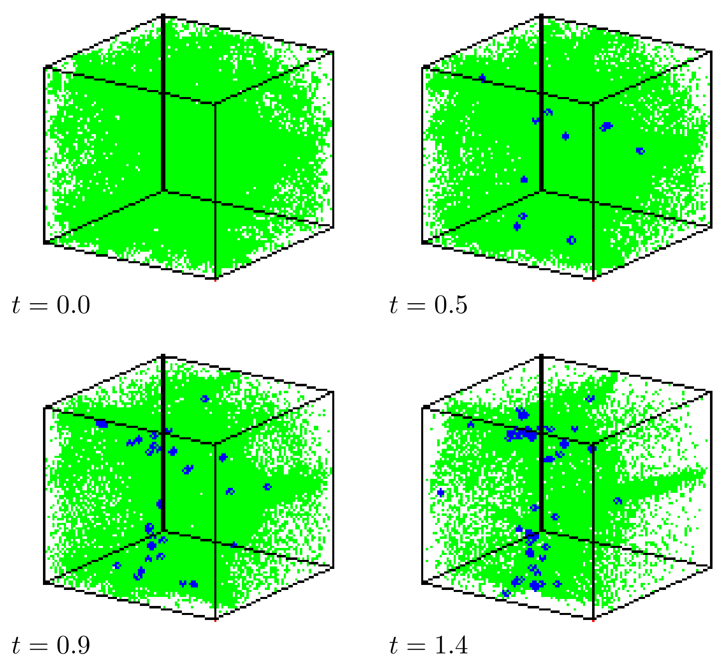

Figure 1. Time evolution and fragmentation of a region of 222 Jeans masses in the interior of a molecular cloud with initial Gaussian density fluctuations having a power law of $P(k) \propto 1/k^2$. Collapse sets in and soon forms a cluster of highly condensed cores, which continue to accrete from the surrounding gas reservoir. At $t = 0.5$ (measured in terms of the free-fall time of the isolated gas cube) about 10% of all the gas mass is converted into protostellar cores, shown as dark points. At $t = 0.9$ about 30% of all gas is accreted and at $t = 1.4$ this value is 65%.

2. A Case Study

As an example, we present in Fig. 1 the time evolution and fragmentation of a region of 222 Jeans masses in the interior of a molecular cloud with initial Gaussian density fluctuations of power law $P(k) \propto 1/k^2$. Pressure smears out small scale features, whereas large scale fluctuations start to collapse into filaments and knots. After about one quarter of the overall free-fall time, the first highly collapsed cores appear and more follow. A hierarchically structured cluster of accreting protostellar objects forms.

Isothermal gas cannot heat, accretion continues until the entire gas reservoir is exhausted. There are no feedback mechanisms in our model, as it concentrates on the interplay between gravity and gas pressure alone. Hence, it is scale free, and can be applied to star forming regions of vastly different properties. When applied to a dark cloud like Taurus-Aurigae, with densities of about $n(H_2) = 100\,\mathrm{cm}^{-3}$ and a temperature of $T = 10\,\mathrm{K}$, Fig. 1 corresponds to a cube of length 5.2 pc and a total mass of 6 300 $\mathrm{M}_\odot$. The time scale is 3.3×10^6 yrs. Comparing with a high mass star star forming region like Orion, i.e. assuming $n(H_2) = 10^5\,\mathrm{cm}^{-3}$ and $T = 30\,\mathrm{K}$, these values scale to $L = 0.28$ pc and $M = 1000\ \mathrm{M}_\odot$. The corresponding time scale is 7.5×10^4 yrs.

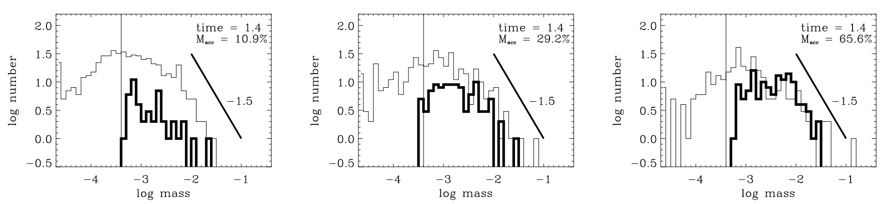

Figure 2. Mass spectrum of cores (thick line) and of identified gas clumps (thin lines) at times $t = 0.5$, $t = 0.9$, and $t = 1.4$. The mass resolution for this simulation with 200 000 particles is indicated by horizontal line at $\log_{10} M = -3.4$

For comparison with observational data, we plot in Fig. 2 the mass distribution of identified gas clumps in the simulation at $t = 0.5$, 0.9 and 1.4 (thin lines). It agrees remarkably well with the distribution in molecular clouds, which is analyzed as following a power law with slope -1.5 for high clump masses (Blitz 1993); this is added as reference in the plot. Furthermore, we show the mass spectrum of the protostellar cores (thick lines).

Typically, cores forming in the most massive clumps tend to populate the high-mass end of the distribution, simply because they have the largest gas envelope to accrete from. However, in detail this is influenced by an additional process. The protostellar cores form a dense cluster, and while gaining mass via accretion, they compete with each other for a common gas reservoir. As cluster members, they strongly interact with each other

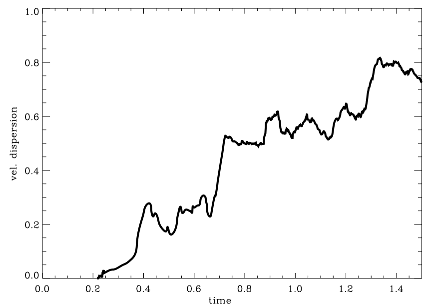

Figure 3. Velocity dispersion of the newly formed cluster of protostellar objects as function of time. For a region like Taurus, the abscissae would be scaled by 1 km/s and the ordinates by 3.3×10^6 yrs. For a Orion-like region, these values are 2.6 km/s and 7.5×10^4 yrs.

dynamically, and as a consequence, a considerable number of cores get expelled from their parental envelopes into low-density regions. This terminates their growth, and determines their position in the mass spectrum.

Under the assumption that every protostellar core forms exactly one star of a given mass fraction, this distribution could be compared with the stellar initial mass function. While there is reasonable agreement for intermediate and high-mass stars, our model produces a deficit of low-mass stars (there appears to be a plateau in the range $-3 \leq \log_{10} M \leq -2$, and a steep fall-off at the resolution limit). This is the case in all our models, regardless of the initial conditions. This fact indicates, that for low-mass star formation additional physical processes are important, and a detailed treatment of protostellar accretion disks is necessary. Furthermore, additional fragmentation might occur in the late accretion phase leading to a binary or multiple system within the same parental gas envelope (see e.g. Burkert et al. 1997)

Figure 3 finally plots the velocity dispersion of the cluster. Again, this value can be compared to the data from young stellar clusters, like in Taurus or Orion. Despite the simplifications in our model, the kinematical properties are in excellent agreement with the observed values.

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